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Bridging Phenomenon in Insulating Liquids

***Abstract**. The article deals with phenomenon of bridging, which occurs in insulation system of high voltage devices which is based on liquid base. This article describes mechanism for creating bridges by dielectrophoresis and magnetophoresis, which is different in few ways. Except these two phenomena, is due to comparison showed similar mechanism of releasing copper ions. For this process is also showed influence of these ions in real HV transformer. Phenomenon of bridging is also described on ferrofluid made from transformer insulation oil and coated Fe_3O_4particles by measurement of dielectric parameters.*

Keywords: transformer oil, bridging, dielectrophoresis, magnetic fluid, dielectric parameters.

Introduction

One of most used insulating systems for power transformers is paper-oil system.Presence of electromagnetic and thermal field during operation of power transformer can cause electro-physical and chemical processes. Consequence of these processes is generation of different substances, such as oxygen, various acids and compounds, cellulose fibers, copper particles (ions) and moisture.Result of presence of these substances in transformer oil is degradation of insulating system, and thus lower electric strength, because of creating inhomogeneous points in insulation.Moreover, some of these substances with higher conductivity can also reduce the insulating properties.Furthermore, when particles of these substances are adsorbed into the insulating paper, the dielectric strength of the paper will be reduced.In insulation systems with presence of nanoparticles (Fe_30_4, TiO_2) there is a risk of interaction between coated nanoparticles and contaminants. [1][2]

Further risk is phenomena of bridging - creation of long chains from small particles in direction of electric or magnetic field.Particles tend to move in direction of field, to places with highest intensity of field.These forces are caused by phenomena of magnetophoresis and dielectrophoresis.It is dependent on specific field, which is acting on particles and also on character of particles.

Solution for reducing risks of creating bridges can be done in many ways. In general, there are mechanical and chemical methods, such as filtering or injecting of inhibitors and adsorbents into volume of degraded fluid.It is dependent on type of dispersed particles.[1][2]

Releasing of copper ions

One of specific cases of creation of foreign substances in insulation system of power transformer is releasing of free copper ions.These ions are created by process of copper dissolution.Dissolution is caused by presence of trace acids in volume of transformer oil. These acids are products of degradation.Other factors which are causing this dissolving are nitrogen compounds, moisture, oxygen, corrosive sulfur etc.From view of creating bridges, these ions are not affecting these processes due to conditions for dielectrophoresis and magnetophoresis.In contrast with bridging, copper ions can create local clusters, due to presence of charge of ions.As result of these facts, resistance and therefore also conductivity can be negatively affected in places of occurrence of copper ions in volume of transformer oil.[1]

Experimentally was found, that volume of copper ions per 1 kg of pure transformer oil can reach approx. 7 mg. This measurement was executed on transformer with voltage rate 110 kV/ 38,5 kV/ 10,5 kV with capacity 31,5 MW.This high concentration affects dielectric losses and volume resistivity. Before start of adsorption process were dielectric losses at value 219.10^{-4} and volume resistivity was $0,67.10^{12}\Omega$.[1]

After adsorption was amount of copper ions approx. 0,5 mg. Dielectric losses were lowered to value 70.10^{-4} and resistivity to $7,05.10^{12}\Omega$.[1]

It should be noted, that degradation by process of copper dissolution is different from bridging. But in both cases there are structural changes in insulation system, which are similar and which leads to degradation of insulating properties.

Magnetophoresis

As was mentioned, one type of mechanism of creating bridges is bridging due to presence of magnetic field. General principles of magnetophoresis can be briefly explained by few equations. Potential energy of a particle can be written as:

(1) $$U = -\frac{(\chi_p - \chi_m)}{2\mu_0} V B^2$$ [1]

Where:
V- Volume of particle
χ_p-Magnetic susceptibilityof particle
χ_m-Magnetic susceptibilityof medium
μ_0– Magnetic permeability of vacuum
B – Magnetic flux density

Equation for magnetic force, which is acting on particle, can be written as:

(2) $$\boldsymbol{F} = -gradU = \frac{(\chi_p - \chi_m)}{2\mu_0} V(\boldsymbol{B} \cdot \nabla) \cdot \boldsymbol{B}$$ [2]

Due to (2) an inhomogeneous magnetic field can create a force, which can act on particle in liquid. The drag force which acts on particle during a movement can be described as:

(3) $$\boldsymbol{F_D} = -6\pi\eta r \boldsymbol{v}$$ [3]

Influence of environment viscosity is given in (3) by η. Thus force acting is directly proportional to viscosity of environment and to radius of particle.[3]

Equation for magnetophoretic velocity can be written as:

(4) $$\boldsymbol{v} = \frac{2}{9}\frac{(\chi_p - \chi_m)}{\mu_0 \eta} r^2 (\boldsymbol{B}\cdot\nabla)\cdot\boldsymbol{B}$$ [4]

This equation shows that velocity of particle is directly proportional to difference between magnetic susceptibility of medium and particle.[3]

Magnetophoresis can be in general divided into two types.Positive magnetophoresis appears in case, when permeability of environment (fluid) is lower than permeability of particles. In this case are particles attracted to local maxima of inhomogeneous magnetic field and repelled from minima. For negative magnetophoresis is necessary, that permeability of environment is higher than permeability of particles.[4]

Dielectrophoresis

Whereas magnetophoresis occurs under influence of magnetic field, for dielectrophoresis is necessary presenceof electric field. This phenomenon can be short described as force acting on particle during exposition of inhomogeneous electric field.

For presence of dielectrophoresis is required presence of inhomogeneous electric field. This field creates a gradient which causes migration of dipole particles. It should be noted, that particles must be dipoles, but they needn't have charge. Degree of dielectrophoresis and thus velocity of particles migration is dependent on particle size and shape, properties of environment and on properties of acting field.[2]

One of the cases of dielectrophoresis is contamination of transformer oil with cellulose fibers. These fibers can be considered like dipoles without charge. Equation for force acting on fibers can be written as [2]:

(5) $$F = \frac{\pi\varepsilon_m\varepsilon_0}{12} D^2 L\left[\frac{\alpha}{\alpha-1} - f(\beta)\right]^{-1}\nabla E^2$$ [5]

In this equation (5) is relative permittivity of environment represented by ε_m. Equation for this model assumes that particles are prolate spheroids with diameter D and length L. Ratio between relative permittivity of fibers and environment is represented by α. Aspect ratio between diameter and length is represented by β.[2]

Migration of particles which is parallel to drag force is given by:

(6) $$F = 3\pi\eta D v g(\beta)$$ [6]

For conductive fiber we can assume that$\varepsilon_f \to \infty$, therefore$\alpha \to \infty$and$\frac{\alpha}{\alpha-1} \to 1$. After combining equations (5),(6) and substituting $\frac{\alpha}{\alpha-1} \to 1$, and taking the limit $\beta \to \infty$ we can write equation for fiber velocity [2]:

(7) $$v = \lim_{\beta\to\infty}\frac{\varepsilon_m\varepsilon_0}{24\eta} L^2 \frac{\ln 2\beta - 0{,}5}{\ln 2\beta - 1}\nabla E^2$$ [7]

The influence of fiber aspect ratio is provided only for β>5. Equally, β must be for this approximation>2. Velocity is directly proportional to square of the length.[2]

Ferrofluid particle structuralisation in power transformer

Particles structuralisation in magnetic fluids, with particle size is approx. 10 nm can be also described by process of magnetophoresis.As mentioned above, in case of ferromagnetic particles (Fe_3O_4) which are suspended in nonmagnetic medium (inhibited transformer oil), it is a positive magnetophoresis.Except bridging due to positive magnetophoresis, there is also possibility of creating bridges because of orientation of nanoparticles into direction of stationary magnetic field. This phenomenon is mainly possible in magnetic fluids, where are nanoparticles dispersed in homogeneous way.

For bridging, hence for creation of long chains is necessary sufficient long time of magnetic fieldpresence.Experimentally was found, that for origin of long chain with length of 100 µm and more is necessary time approx. 100 s.

In case of usage of these fluids as coolant in power transformer, it must be mentioned, that in this case, except presence of magnetophoresis is there also present phenomenon of thermomagnetic convection.Condition for this phenomenon is presence of temperature gradient and magnetic field. For use in cooling system of power transformer are conditions for thermomagnetic convection satisfied. The source of temperature gradient is heat produced by AC current in windings. Thus heat generated by winding and core of transformer creates in area inhomogeneous magnetic field and temperature gradient.

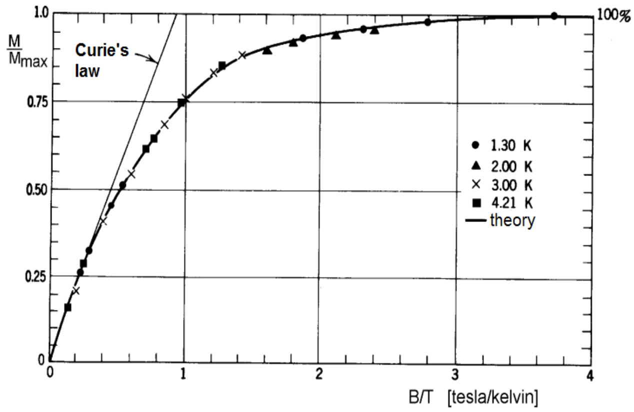

Fig.1. Langevin function for M=f(t) [5]

Magnetization of magnetic fluid is dependent on the value of magnetic field intensity and as well as on the carrier medium susceptibility. In a magnetic fluid where are present varying temperatures, the susceptibility is a function of the temperature as is showed on figure 1.[5]

One of advantage of thermomagnetic convection is the transmission velocity of heat from inside of power transformer to walls of the vessel and dissipation of heat to surrounding environment determines highest currents in the windings therefore in part determines a size and weight of power transformer for a given power. Accordingly more efficient cooling could bring smaller dimensions of power transformers and less amount of cooling fluid. Equally important is decreasing of windings temperature, which can be decreased up to 10%. Limit factor is a viscosity of these used magnetic fluids, because too dense magnetic fluid will not get into every layer of oil - paper insulation system.[6]

Bridging of cellulose fibers under applied DC voltage

For confirmation of theory which is given above, are in this chapter showed two examples of influence of DC voltage and time, which are acting on particles.For the purpose of the demonstration is not necessary to give all details about carrier fluid and cellulose fibers. Details can be found in original article which is here cited [2].

As is shown in equation (5), force which is acting on particle under influence of inhomogeneous electric field is directly proportional to square of intensity of this field. Measurement was realized for three voltage levels from 2 kV to 15 kV, and application time was in every case 600 s. Also the concentration of cellulose fibers was same in all samples. The results are shown at figure 2.[2]

Applied voltage significantly affects amount of cellulose fibers between electrodes.It has to be mentioned, that after 600 s is difference between amount of fibers well recognizable, but after sufficient long time, between every electrodes will be the same amount of fibers.So the voltage level changes only dynamic of this process. [2]

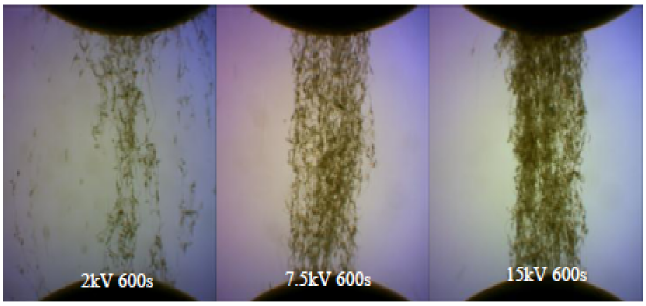

Fig.2. Dielectrophoretic bridging of cellulose fibers under applied DC voltage [2]

Dynamics of this process is shown on figure 3, where is DC voltage set to 7,5 kV and pictures were taken three times, after 10 s, 90 s and 600 s.At first figure after acting of voltage for 10 seconds are visible only small clumps of fibers around electrodes and few clusters of fibers in direction of electric field, between electrodes.After 90 seconds clusters began to emerge.But after 600 seconds, is whole area between electrodes filled up with clusters from fibers.[2]

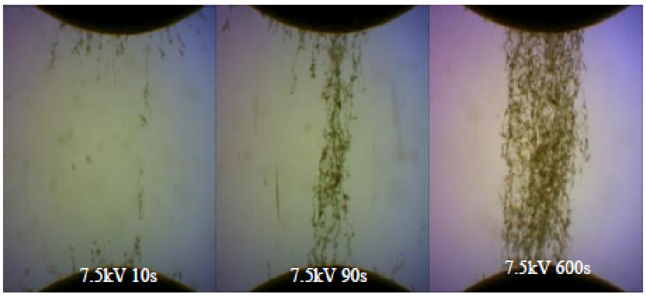

Fig.3. Dielectrophoretic bridging of cellulose fibers under applied DC voltage after different time [2]

Bridging of Fe_3O_4 nanoparticles in ferrofluid

Behavior of magnetic nanoparticles in magnetic fluids is similar to behavior of cellulose fibers.Difference is in case, when these fluids are exposed also to thermal field.Then is influence of thermomagnetic convection significant, because magnetophoresis can invoke drag force against forces of thermomagnetic convection.So for investigation of bridging phenomenon, is necessary to expose specimen only to magnetic field.

On figure 4 are shown clusters of Fe_3O_4 dispersed in water-based magnetic fluid.These clusters were created by pulse magnetic field with induction 40 T.this case is extraordinary for presentation of creating clusters in short time.[7]

On figure 5 are shown similar cluster like on figure 4, but these clusters were created by steady magnetic field with induction of 40 mT in transformer oil. Capacitors and resistors which are shown, theoretically describes dielectric model between electrodes in this case. These clusters may have influence to dielectric parameters such as dielectric strength and dielectric losses.[8]

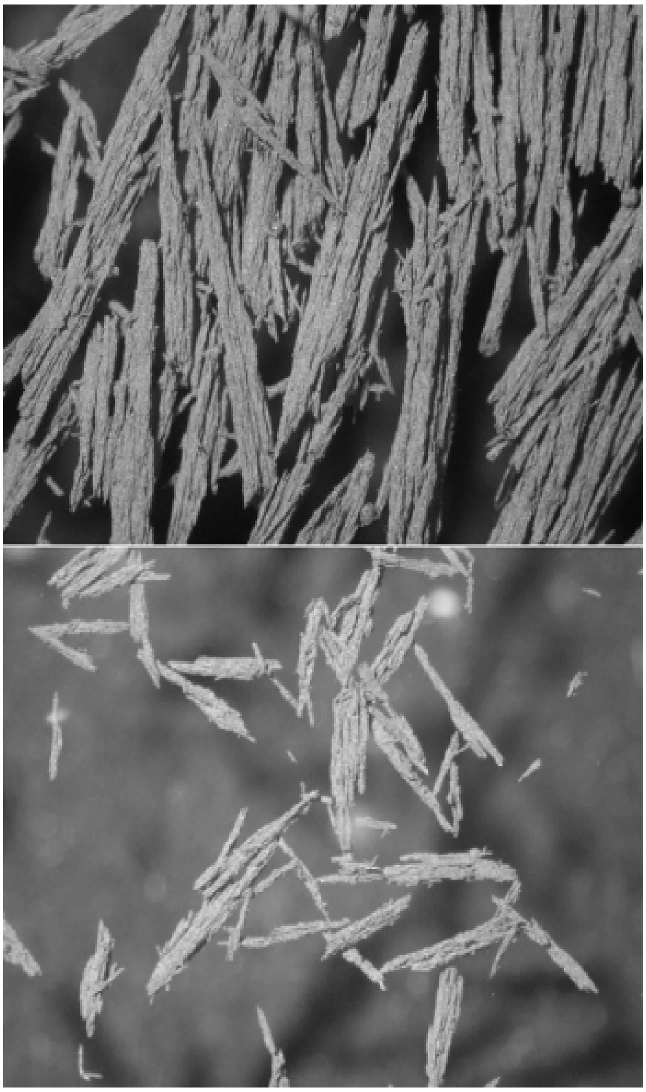

Fig.4. Clusters of Fe_3O_4 created by magnetic pulse with induction 40T [7]

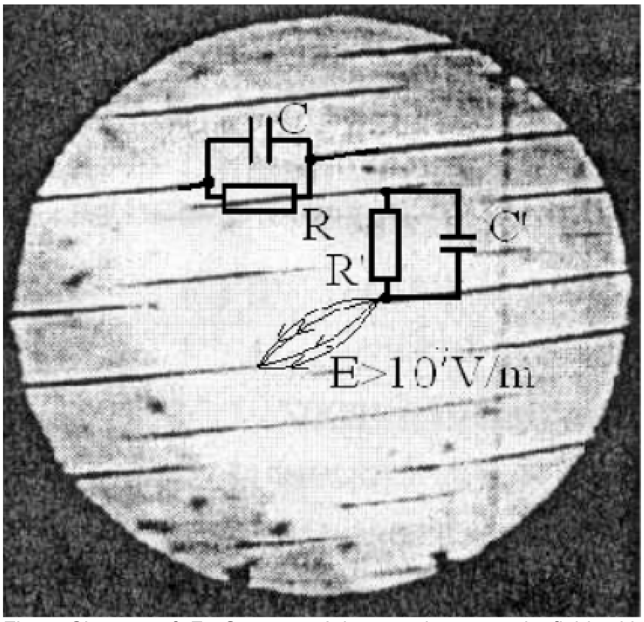

Fig.5. Clusters of Fe_3O_4 created by steady magnetic field with induction 40 mT [8]

Experiment

For confirmation of bridging phenomenon are in this chapter shown two measurements.Both of them are based on dielectric spectroscopy, which allows in many ways recognize structural changes in dielectric structure.Experiment was performed on sample with concentration of magnetic nanoparticles approx. 1%.Sample was based on inhibited transformer oil with added oleic acid as surfactant.

Specimen was placed in vessel made from PTFE in which was placed electrode system composite from Rogowski electrode system. External magnetic field was created by pair of permanent NdFeB magnets with magnetic induction 40 mT. Magnetic induction at place of electrodes was measured by Hall effect sensor. Diameter of electrodes was 20 mm and gap between electrodes was set for measurement to 1 mm. The measurement was realized bystandard temperature 20°C. Assignment of capacitance and dissipation factor was made by LCR meter in frequency range from 100 Hz to 2 MHz.

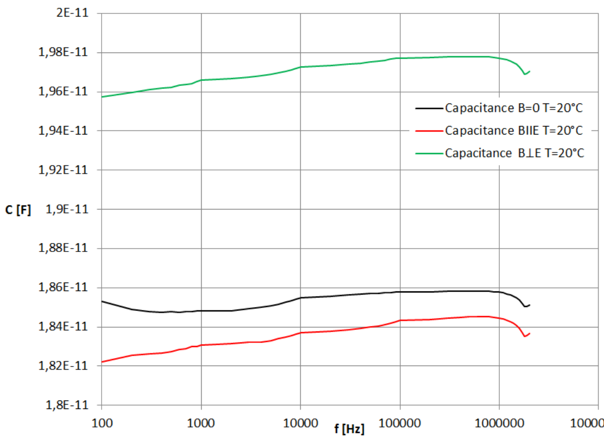

Fig.6. Frequency dependence of capacitance and influence of bridging phenomenon

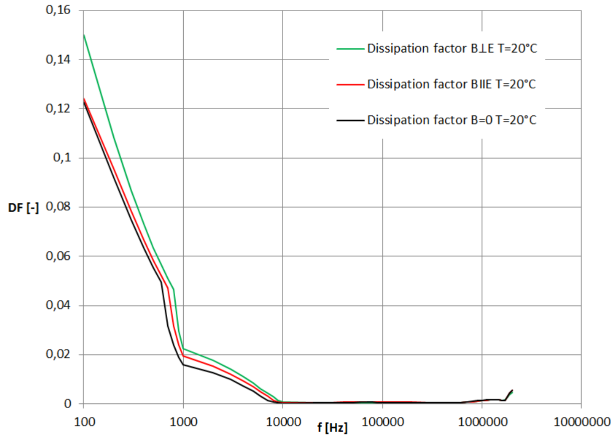

Fig.7. Frequency dependence of dissipation factor and influence of bridging phenomenon

As is shown on figure 6, anisotropy of capacitance is strongest in case of acting of perpendicular magnetic field. This is caused by fact that magnetophoretic force is stronger than dielectrophoretic force, which is acting in direction of electrode axis. Thus this force is creating a long chain which affects dielectric constant, which is proportional to capacitance.

On figure 7 are shown curves for dissipation factor. It is observable, that by lower frequencies approximately less than 1 kHz is dissipation factor too high. It's caused by polarization losses of magnetic nanoparticles, which are rotating into direction of acting electric field. For higher frequencies particles can't follow changes of acting electric field, thus the dielectric losses are decreased.

Conclusion

Mechanism of bridging phenomenon is different for conventional fluids and for magnetic fluid. It is caused by different mechanism for acting of electric field and acting of magnetic field.But in both cases is dynamics of this phenomenon strongly affected by intensity of electric or magnetic field.It is shown in equations for drag force, where this force is directly proportional to square of intensity of acting fields (B,E).Also particles which are used to creation of bridge can affect dynamics and degree of this process.It is represented by dimensions of these particles, what directly affects the velocity of these particles and thus speed of bridge creation.

In conventional fluid it's necessary to prevent bridging by decreasing concentration of contaminants. In case of usage of magnetic fluids in devices as coolants, is risk of bridging lower, due to presence of thermomagnetic convection, which forces are acting against forces of magnetophoresis.

Influence of bridging phenomenon in magnetic fluid was confirmed by measurement of capacitance and dissipation factor. In both cases are changes in dielectric structure sufficiently strong to affect dielectric parameters in wide frequency range.

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